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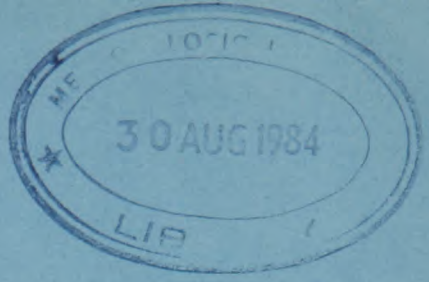

METEOROLOGICAL OFFICE

Scientific Paper No. 25

The Relation between Beaufort Force Wind Speed and Wave Height

by R. FROST, B.A.

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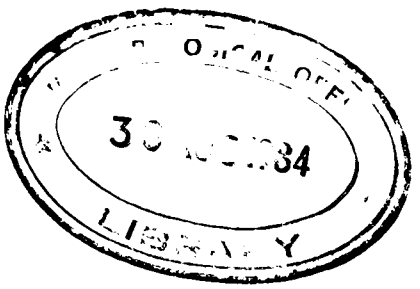

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The Relation between Beaufort Force Wind Speed and Wave Height

by R. Frost, B.A.

INTRODUCTION

Observations of wind speed and wave height at sea are normally made by visual observations of the appearance of the sea as few ships are fitted with anemometers and even fewer with wave recorders.

The wind force at sea is expressed on a scale of 0–12 devised by Captain, afterwards Admiral, Beaufort in 1806. Originally this scale defined the wind force in terms of the canvas carried by a fully rigged frigate, but with the passing of sail the practice arose of judging the wind force from the state of the sea surface. In 1939 as a result of a detailed study of the problem by the Commission for Maritime Meteorology, the International Meteorological Committee agreed to the use of a criterion by which the wind force is estimated from the appearance of the sea surface and this is given in Table I.

TABLE I. *Beaufort Scale of Wind Force*

Beaufort Wind Force	Mean Wind Speed in knots Measured at a height of 33 ft above sea level	Limits of Wind Speed in knots Measured at a height of 33 ft above sea level	Descriptive Term	Sea Criterion	Probable Height of Waves in metres*	Probable Maximum Height of Waves in metres*
0	0	Less than 1	Calm	Sea like a mirror.	—	—
1	2	1–3	Light air	Ripples with the appearance of scales are formed, but without foam crests.	0·1	0·1
2	5	4–6	Light breeze	Small wavelets, still short but more pronounced, crests have a glassy appearance and do not break.	0·2	0·3
3	9	7–10	Gentle breeze	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	0·6	1·0
4	13	11–16	Moderate breeze	Small waves, becoming longer; fairly frequent white horses.	1·0	1·5
5	19	17–21	Fresh breeze	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray.)	2·0	2·5

* These columns are added as a guide to show roughly what may be expected in the open sea, remote from land. In enclosed waters, or when near land with an off-shore wind, wave heights will be smaller, and the waves steeper.

TABLE I *continued*

Beaufort Wind Force	Mean Wind Speed in knots Measured at 33 ft above sea level	Limits of Wind Speed in knots a height of sea level	Descriptive Term	Sea Criterion	Probable Height of Waves in metres*	Probable Maximum Height of Waves in metres*
6	24	22–27	Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)	3·0	4·0
7	30	28–33	Near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	4·0	5·5
8	37	34–40	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.	5·5	7·5
9	44	41–47	Strong gale	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.	7·0	10·0
10	52	48–55	Storm	Very high waves with long overhanging crests. The resulting foam in great patches is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. Tumbling of the sea becomes heavy and shock like. Visibility affected.	9·0	12·5
11	60	56–63	Violent storm	Exceptionally high waves. (Small and medium-sized ships might be for a time lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11·5	16·0
12	—	64 and over	Hurricane	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	14 or over	—

Notes

(1) It must be realized that it may be difficult to estimate wind force by the sea criterion. The wind force and direction may therefore be estimated by other means, e.g. the "feel" of the wind or the smoke, making due allowance for course and speed of ship (see Marine Observer's Handbook, London, HMSO, 1963, Table XXII).

(2) The lag effect between the wind getting up and the sea increasing should be borne in mind.

(3) Fetch, depth, swell, heavy rain and tide effects should be considered when estimating the wind force from the appearance of the sea.

It is clear from this table that the Beaufort Scale, which defines the wind force by the effect it has on the sea surface, is not a scale of speed, a point which has not always been realized, and one object of this paper is to see whether it is possible to specify the wind flow which will cause the effect observed. Furthermore the internationally agreed wind equivalents and the suggested wave-height equivalents of the Beaufort numbers are not compatible with the wind/wave relationships obtained by oceanographers and a second object of the present paper is to see whether it is possible to derive a set of self-consistent relationships between these variables.

HISTORICAL SUMMARY

Many attempts have been made by meteorologists to determine wind speed equivalents of the Beaufort Scale and these have been discussed by Verploegh[1]* and are briefly summarized here.

At the beginning of this century several series of equivalents were in use but by 1913 only two had survived and were in general use, namely the Seewarte series constructed by Köppen in 1898 and the Meterological Office series constructed by Simpson in 1906. By 1915 the former series was in general use over most of Europe whilst the latter was in use in England and Russia. These two series are exhibited in Table II.

TABLE II. *Equivalent speeds in metres per second*

Beaufort No.	0	1	2	3	4	5	6	7	8	9	10
Seewarte series	0	1·7	3·1	4·8	6·7	8·8	10·7	12·9	15·4	18·0	21·0
Simpson 1906 series	0	0·8	2·4	4·3	6·7	9·4	12·3	15·5	18·9	22·6	26·4

The former series can be fitted very closely by the power law

$$V = 1{\cdot}35\, B^{7/6} \quad \ldots \quad (1)$$

where V is the wind speed in m/s and B the Beaufort force whilst the latter is based on the power law

$$V = 0{\cdot}836\, B^{3/2} \quad \ldots \quad (2)$$

which Simpson found to give the best fit to his observations.

As it was clearly undesirable to have two such different wind equivalents for the Beaufort numbers the International Meteorological Committee in 1926 accepted a compromise proposal by Simpson in which he put forward a series obtained by averaging in a rather special way the above two series. This compromise did not however prove satisfactory and in 1946 the International Meteorological Committee decided to replace the equivalents agreed upon in 1926 by the original Meteorological Office series of 1906.

In 1956 Verploegh suggested a new set of equivalents based on the results of all earlier major studies and this together with the earlier equivalents is shown in Table III.

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* The index figures refer to the bibliography on page 12.

TABLE III. *Survey of old and new determinations of the equivalent velocities (in m/s) to the Beaufort estimates of the wind force at sea (after Verploegh[1])*

Beaufort number	1	2	3	4	5	6	7	8	9	10	11	Exposure (m)
I. Simpson 1906, corrected	1·2	2·9	5·3	7·8	10·4	12·8	15·2	18·2	22·6	25·5		10–13
II. Krümmel (*Gazelle*; 1874–76)		3·2	4·9	6·8	9·3	11·0	14·1	16·7	19·9	23·4		± 6
III. Waldo (1888)	2·2	3·1	5·4	7·3	10·2	13·3	15·5	17·0	19·2			9 and 26
IV. Gallé (1914)	2·2	3·5	5·5	7·8	10·1	12·2	14·4					7 and 12
V. *Meteor* (tropics) (1925–27) corrected by −0·5 m/s		3·6	5·6	7·7	9·9	11·9	(13·8)					32
VI. *Meteor* (higher S. Lat.) corrected by −1·0 m/s		(3·0)	6·5	9·0	11·6	14·4	17·3	20·1	22·5			32
VII. *Schwabenland–Friesenland* (1936–37) corrected by −0·3 m/s	2·6	4·3	6·1	7·9	10·0	11·7	(13·5)					
VIII. *Texel–Tersch. bank* (1951)	1·3*	3·2*	5·8	7·9	10·2	12·4	14·4	(16·8)				7
IX. German light-vessels (1950)	1·3*	3·2*	6·1	7·8	9·9	12·1	14·1	16·3	17·9	20·1	25·8	20
Mean	(1·3)†	3·4	5·7	7·8	10·2	12·4	15·0	17·7	20·4	23·0	25·8	
Adopted mean $V=1{\cdot}51B^{1{\cdot}18}$m/s	1·5	3·4	5·6	7·8	10·2	12·6	15·1	17·7	20·4	(23·1) 23·3‡	(25·8) 26·5‡	10–15
Meerkatze (1953) Indifferent atmosphere	1·8	3·7	5·6	7·8	9·9	12·4	(15·0)					19

* Reduced to an exposure at 10m. † Light-vessels and coastal stations only. ‡ Computed with the help of a graphical extrapolation of the series extending to at least 9*B*. The values in brackets of the constituting series have not been used in the averaging process.

This series, which was formed by taking the arithmetic mean of nine sets of equivalents including Simpson's original data, and some from the 19th century which were of doubtful accuracy and most of which showed considerable differences amongst themselves, has not yet been accepted by the World Meteorological Organization.

When Verploegh plotted his equivalents against the Beaufort numbers he obtained the following functional relationship between the wind equivalents in m/s and the Beaufort numbers

$$V = 1{\cdot}51\, B^{1{\cdot}18} \quad . \; . \; . \quad (3)$$

the power index of which is very similar to that of the Seewarte series.

Verploegh considered that the different relationship obtained by Simpson was due in part to the varying exposures of the anemometers at the five stations which were used in deriving the Meteorological Office series and argued that Simpson was at fault in averaging the results from these stations in the way he did, i.e. in treating the estimates as though they had all been made at the same place and by the same observer. He therefore formed a 'corrected' Simpson's series by averaging the mean equivalents from each of the five stations, which undoubtedly had the effect of bringing the 'corrected' Simpson series more into line with the Seewarte series. Apart however from producing this result the reasons for adopting this procedure are not clear for it reduced the predominant effect of the observations from Scilly and Gorleston, where the anemometers had the best exposures and where the states of the sea could be clearly observed, and overemphasized the effect of the observations at North Shields and Oxford, where the exposures of the anemometers were not so good and where at one station it was not even possible to observe the state of the sea. Furthermore at the last two stations there were in all only 52 observations for all Beaufort numbers above force 5 which are clearly inadequate for the derivation of reliable means. It would seem therefore that the explanation as to why the Meterological Office series, which has been adopted internationally, differs from most other sets lies elsewhere and the probable reason for this is discussed in a later section.

Inspection of Table III also shows that supporting evidence for Verploegh's equivalents for Beaufort numbers above force 8 is not very strong. Simpson's 'corrected values' for example are some 5 m/s higher than the observations from the German light-vessels. Furthermore the mean equivalents from the latter show an increasing divergence from Verploegh's equivalents at all Beaufort numbers from 4 to 10 amounting to 2·9 m/s at force 10, an amount which is greater than the difference between any two consecutive numbers, yet for Beaufort force 11, for which no other sets of means are available, Verploegh adopted the mean from the German light-vessels without correction.

One other rather curious feature of Table III is the fact that the mean wind speeds from the Dutch light-vessels, whose anemometers were about 7 m above sea level, are almost the same as those from the German light-vessels whose anemometers were about 20 m above the sea. As the anemometers in the former were mounted at a height of 1·5 m above the wheel-house this suggests that in flowing over the wheel-house the winds were accelerated so making the 'effective' height of the Dutch anemometers nearer 20 m than 7 m.

RELATION BETWEEN BEAUFORT FORCE AND WAVE HEIGHT

If the values in metres of H_{max}, the maximum wave heights, and H_{mean}, the mean wave height given in Table I are plotted against the Beaufort numbers on double logarithmic paper (see Figure 1) it can be seen that

$$H_{max} = 6{\cdot}0 \times 10^{-2}\, B^{7/3} \quad . \; . \; . \quad (4)$$

$$H_{mean} = 4{\cdot}5 \times 10^{-2}\, B^{7/3} \quad . \; . \; . \quad (5)$$

so that

$$H_{mean} = \tfrac{3}{4}\, H_{max}. \quad . \; . \; . \quad (6)$$

Mean values of wave heights in the North Sea for various values of the Beaufort numbers were discussed by Petri[2] and are plotted in Figure 1. These show good agreement with the values proposed by the International Meteorological Committee for Beaufort numbers 4 and above but for low numbers the wave heights are too high. Whilst it was Petri's aim, when analysing the observations, to include as far as possible only wind waves, he found it difficult to exclude cases in which the direction of the swell more or less coincided with the prevailing direction of the wind and he concluded that the accidental inclusion of the swell in wind/wave observations resulted in the mean value of both the wave height and period being too high in the case of low wind forces.

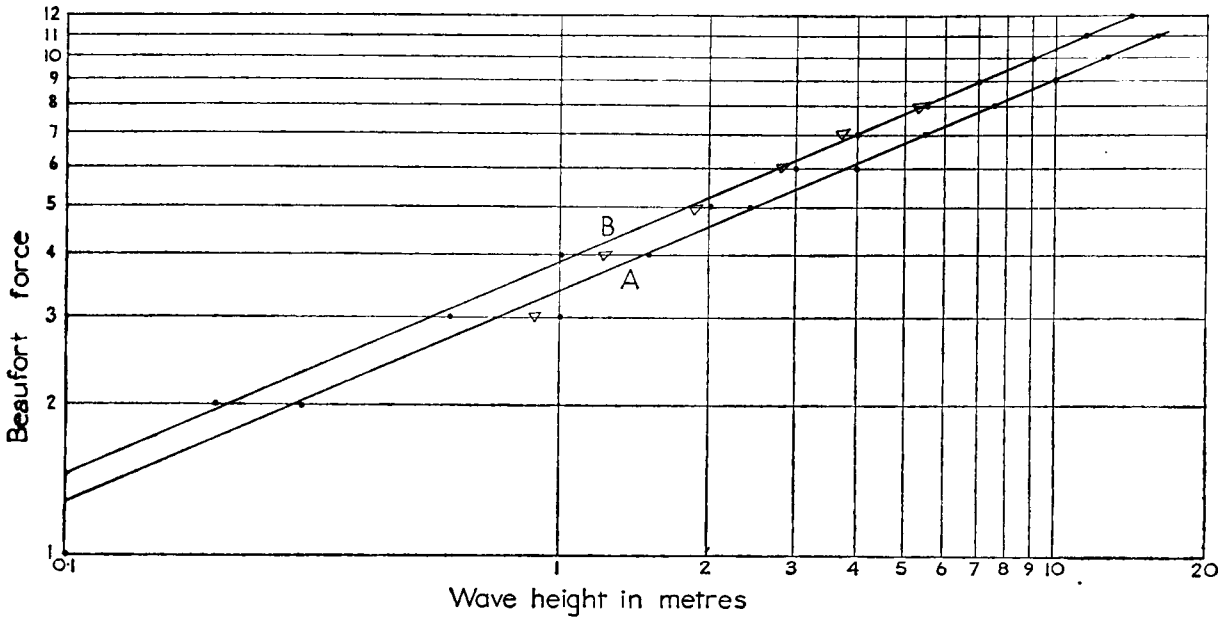

FIGURE 1. Relationship between wave height in metres and Beaufort force.
A: maximum wave height; B: mean wave height; ▽ : mean wave heights in the North Sea.

RELATION BETWEEN WIND SPEED AND WAVE HEIGHT

When a wave recorder is used to register the up-and-down movement of the sea it is possible to calculate from its record the component simple waves of the wave system and from these to compute a value H, which is defined as the height of a periodic wave having the same total energy as that of the wave system concerned. From statistical considerations Longuet-Higgins[3] derived a relationship between H_{max}, the probable height of the highest wave out of a total of N waves, and H. For $N = 400$ the relationship is

$$H_{max} = 2{\cdot}58\, H \qquad . \; . \; . \quad (7)$$

or if it is assumed that the average period of the waves is about 9 seconds then H_{max} is the most probable height of the highest wave in a 60-minute interval.

One hundred and ten wave records selected from those taken by the Ocean Weather Ship *Weather Explorer* and analysed by the National Institute of Oceanography were discussed by Darbyshire.[4] The wave records were so chosen that the effect of extraneous swell was insignificant and the waves recorded were almost entirely wind waves. The fetch varied from 200 to 2000 nautical

miles, the duration from 4 to 48 hours and the Beaufort forces from 3 to 11. Over this range of the Beaufort numbers Darbyshire found that

$$H=8{\cdot}1\times10^{-3}\ W^2 \quad . \ . \ . \quad (8)$$

where H was the wave height in feet and W, the wind speed measured at an anemometer height of 66 feet, was in knots.

From equations (7) and (8) converting H to metres and W to metres per second

$$H_{max}=2{\cdot}40\times10^{-2}\ W^2. \quad . \ . \ . \quad (9)$$

RELATION BETWEEN WIND SPEED AND THE BEAUFORT NUMBERS

If it is assumed that the probable maximum wave heights given in Table I also refer to a 60-minute interval then eliminating H_{max} between equations (4) and (9) gives

$$W^2=2{\cdot}50\ B^{7/3} \quad . \ . \ . \quad (10)$$

$$\text{or } W=1{\cdot}58\ B^{7/6} \quad . \ . \ . \quad (11)$$

so that if the wind is measured at a height of 20 m above the sea the wind equivalents of the Beaufort numbers should be given by equation (11). It is of interest to note that the power index in (11) is the same as that in the Seewarte and Verploegh series whilst the constants of proportionality increase with the height above the surface at which the wind speed is measured.

In a theoretical discussion of the variation of wind speed with height Frost[5] showed that in the first 30 m or so above the sea the wind profile could be closely represented by a simple power law of the height above the surface where the power index was a linear function of the temperature difference between two heights, varying from a value of about 1/7 with very unstable lapse rates to a value of about 1/3 in conditions of moderate stability, with a mean value of about 1/5.

If we assume that Darbyshire's values apply in the mean case and if W_Z is the mean wind speed at a height of Z metres above the surface of the sea then

$$W_{20}=W_{10}\left(\frac{20}{10}\right)^{1/5}=1{\cdot}58\times B^{7/6} \quad . \ . \ . \quad (12)$$

$$\text{or } W_{10}=1{\cdot}38\times B^{7/6} \text{ approximately} \quad . \ . \ . \quad (13)$$

The values of the wind equivalents at 10 m and 20 m above the sea for different values of the Beaufort numbers calculated from equations (11) and (13) are given in Table IV.

TABLE IV. *Theoretical equivalent speeds*

Beaufort No.	0	1	2	3	4	5	6	7	8	9	10	11	12
						metres per second							
Wind equivalent at 20 m	0	1·6	3·5	5·7	8·0	10·3	12·8	15·3	17·9	20·5	23·2	25·9	28·7
Wind equivalent at 10 m	0	1·4	3·1	5·0	7·0	9·0	11·2	13·4	15·6	17·9	20·3	22·6	25·1

It can be seen that the wind equivalents at 10 m are very close to those of the Seewarte series whilst the wind equivalents at 20 m are close to those of Verploegh's series although the latter are stated to be applicable to winds measured at a height of 10–15 m. The reason for this statement however is not clear, for, as can be seen from Table III, the sets of observations which Verploegh used in obtaining his equivalents were made at heights varying between 6 and 32 m over the sea or in some cases at uncertain heights over the land.

In order to test equation (11) further, independent observations of Beaufort force and wind speeds made on British Ocean Weather Ships between 1960 and 1964 were analysed and the results are shown in Table V.

TABLE V. *Speeds equivalent to the Beaufort estimates at sea*

Beaufort force	1	2	3	4	5	6	7	8	9	10	11	12
	metres per second											
Equation (11)	1·6	3·5	5·7	8·0	10·3	12·8	15·3	17·9	20·5	23·2	25·9	28·7
Mean wind speed OWS	1·6	3·9	5·6	7·8	10·2	12·6	15·0	17·8	21·6	24·4	27·4	29·0
No. of observations	50	140	366	539	539	588	656	454	146	38	13	9

The agreement in general is very good except at Beaufort numbers 9, 10 and 11. It appears therefore that a satisfactory relationship between the wind equivalents, meaned without regard to stability, and the Beaufort numbers is given by

$$W_Z = 1{\cdot}38 \left(\frac{Z}{10}\right)^{1/5} B^{7/6} \quad . \quad . \quad . \quad (14)$$

which, if the winds are measured at a height of 10 m above the sea, reduces for all practical purposes to the Seewarte series.

The form of the equation suggests that if stability is taken into account the functional relationship should be of the form

$$W_Z = Z^{-m} A B^p \quad . \quad . \quad . \quad (15)$$

where A and p may be functions of m and this is examined in the following section.

STABILITY OF THE AIR AND THE BEAUFORT SCALE

H.U. Roll[6] carried out a series of observations on the *Meerkatze* in the North Sea and North Atlantic in order to obtain some sets of Beaufort equivalents under various stability conditions and his results are exhibited in Table VI.

TABLE VI. *Wind equivalents under various stability conditions (Meerkatze)*

Beaufort numbers	0	1	2	3	4	5	6
$T_{air}-T_{sea}$	*metres per second*						
−2°C	0	1·4	3·1	5·0	6·9	9·1	11·5
−1°C	0	1·5	3·3	5·1	7·0	9·2	11·8
0°C	0	1·8	3·7	5·7	7·8	9·9	12·4
1°C	0	2·1	4·3	6·3	8·3	10·4	12·8

According to this table not only do the wind equivalents change with stability but also the rate of change of the wind equivalents.

If these observations are plotted on double logarithmic paper (see Figure 2) the lines of best fit are $W(-2)=1{\cdot}35\ B^{1{\cdot}17}$, $W(-1)=1{\cdot}50\ B^{1{\cdot}11}$, $W(0)=1{\cdot}78\ B^{1{\cdot}07}$ and $W(1)=2{\cdot}10\ B$, respectively, which can be fitted very simply by

$$W(T_{air}-T_{sea}) = 9^m B^{\frac{4}{3(1+m)}} \quad . \quad . \quad . \quad (16)$$

where $m=1/7$, $1/5$, $1/4$, and $1/3$ respectively,
or, since these winds were measured at a height of 19·3 m,

$$W_{10}(T_{air}-T_{sea}) = \left(\frac{90}{19{\cdot}3}\right)^m B^{\frac{4}{3(1+m)}} = (4{\cdot}66)^m B^{\frac{4}{3(1+m)}} . \quad . \quad . \quad (17)$$

If this functional relationship is correct then the factor of proportionality would be independent of m at about 2·1 m, and at that height in a stable atmosphere the Beaufort numbers would be numerically the same as the wind speed equivalents.

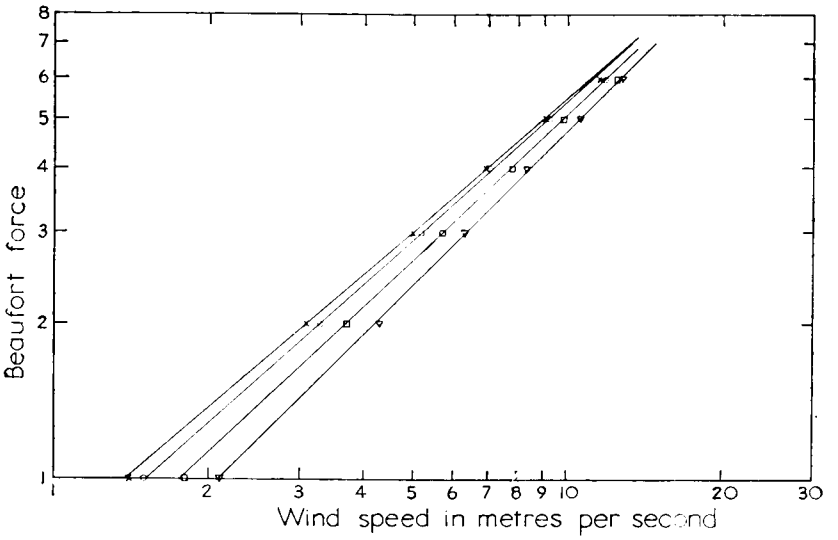

FIGURE 2. Relationship between Beaufort force and wind speed equivalents under various stability conditions

$\times : T_{air}-T_{sea}=-2°C$; o: $T_{air}-T_{sea}=-1°C$;
$\square : T_{air}-T_{sea}=0°C$; $\nabla : T_{air}-T_{sea}=+1°C$.

Verploegh[1] who also carried out a similar investigation on the effect of stability on the wind speed equivalents found no variation of the wind speed equivalents with stability. In all he used 1366 observations, or almost twice the number used by Roll, but stated that the quality of the routine observations on board the Dutch vessels was not as good as that of the observations made during the special research programme on the *Meerkatze*. The conclusions however from this investigation are that at some height, which owing to the poor exposure of the anemometers is uncertain, both A and p in equation (15) are independent of m.

In order to test this further the observations made on the British Ocean Weather Ships which are summarized in Table V were grouped according to stability and the results are shown in Table VII.

TABLE VII. *Wind equivalents in m/s under various stability conditions (OWS)*

Beaufort numbers	0	1	2	3	4	5	6	7	8	9	10	11	12
$T_{air}-T_{sea}$ °C													
−2°	0	1·6	3·7	5·6	7·8	9·8	12·4	14·9	18·0	21·9	24·2	26·8	29·1
		(14)	(38)	(100)	(136)	(183)	(278)	(278)	(223)	(95)	(29)	(9)	(8)
−2° to −1° ..	0	1·4	3·3	5·6	8·0	10·2	12·7	14·6	17·8	21·6	25·2	28·3	—
		(9)	(25)	(77)	(104)	(118)	(118)	(104)	(79)	(15)	(6)	(2)	(1)
−1° to 0°	0	1·5	4·2	5·4	7·8	10·2	12·7	14·8	17·3	21·3	—	—	
		(7)	(43)	(96)	(158)	(111)	(118)	(124)	(70)	(21)	(1)	(1)	
0° to 1°	0	3·3	4·0	5·8	8·3	10·1	12·8	15·1	17·8	21·1	24·7	—	
		(5)	(30)	(71)	(123)	(106)	(94)	(119)	(69)	(13)	(2)	(1)	
1°	0	0·6	3·8	5·8	8·3	10·5	13·3	14·9	18·1	22·4			
		(5)	(4)	(22)	(18)	(21)	(61)	(31)	(13)	(2)			

The number of observations is shown in brackets.

The temperature differences are similar to those in the *Meerkatze* investigation but as in the British ships the air temperatures were measured at a height of 10 m above the sea whereas on the *Meerkatze* the air temperatures were measured at a height of 16·5 m above the sea, the stability conditions may not be quite the same in the two investigations. The wind measurements were made at a height of 20 m on the Ocean Weather Ships and at 19·3 m on the *Meerkatze* and approximately 3500 observations were used in deriving this table, or nearly five times the number used by Roll.

According to Table VII the wind equivalents show little change with stability although there is a slight increase in the wind speed equivalents with change from unstable to stable conditions. This small stability effect would be eliminated if the winds were measured at a height of 15 m above the surface and would be reversed if the winds were measured at a height of 10 m. At the latter height the wind speed equivalents would be about 0·5 m/s lower than those in unstable conditions. As with the Dutch observations the Ocean Weather Ship observations show no rate of change of the wind speed equivalent with stability. Thus the Dutch and British observations both suggest that p is independent of the stability and that A is independent of the stability at a height of about 15 m in the case of the British ships and at some uncertain height exceeding 7 m in the case of the Dutch ships, whereas the very much smaller number of observations from the *Meerkatze* suggests that both A and p vary with stability. It is difficult to give an explanation of this difference.

The effect of possible differences of stability due to the different heights at which the air temperatures were taken can be ruled out because such an effect should be most apparent in stable conditions whereas in fact the reverse occurs. The *Meerkatze* was operating in colder waters than either the Dutch or British ships and so the densities both of the sea and air are greater at the former. The increased density of the water would require the wind equivalents from the *Meerkatze* to be greater than those of the Dutch and British equivalents for the same Beaufort numbers and not the reverse so that the differences (assuming that they are real) are more likely to be associated with the difference in air densities.

The differences are so small however that for all practical purposes the wind equivalents at heights between 10 and 15 m may be considered to be independent of the stability.

DISCUSSION OF THE PRESENT INTERNATIONAL EQUIVALENTS

It has already been shown that the wind equivalents of the Beaufort numbers in the Seewarte series, the Verploegh series and the present series can all be fitted by a similar power-law relationship and that any differences in the constants of proportionality can be reconciled by reducing the wind measurements to a common height. The World Meteorological Organization series, which is based on the Meterological Office series, is out of step with the others and all previous attempts to explain this away have been unsatisfactory. As already stated the Meteorological Office series is largely dominated by the observations from Scilly and Gorleston, and since the exposures of the anemometers at these two stations were good and the observations of the state of sea were made by competent observers, there seems to be no good reason for rejecting these observations in favour of less reliable ones. If therefore the wind and sea observations from Scilly and Gorleston are accepted then it follows that for the same state of sea the wave heights must be different in coastal waters and in the open oceans. This in fact is stated in the footnote to Table I but its implications have been ignored.

Darbyshire in his discussion of wave spectra found that in the open oceans the relationship between wind speed and wave height was given by equation (8) but that in coastal waters their relationship was given by

$$H_{max}=1{\cdot}25\times10^{-1}\,y^{3/2}\,W^{3/2} \qquad . \; . \; . \quad (18)$$

where H_{max} is in feet, W, which is measured at a height of 20 m, is in knots whilst y is a non-dimensional quantity which is a function of the fetch varying from a value of about 0·76 for a fetch of 40 km to a value of about 0·94 for fetches in excess of 150 km.

Converting H_{max} and W to metres and metres per second respectively

$$H_{max}=1{\cdot}03\times10^{-1}\ y^{3/2}\ W^{3/2} \quad . \ . \ . \quad (19)$$

but from equation (5)

$$H_{max}=6\times10^{-2}\ B^{7/3}$$

and hence

$$y^{3/2}\ W^{3/2}=5{\cdot}83\times10^{-1}\ B^{7/3} \quad . \ . \ . \quad (20)$$

$$\therefore \quad yW=6{\cdot}98\times10^{-1}\ B^{14/9} \quad . \ . \ . \quad (21)$$

or if W is measured at a height of 10 m

$$yW_{10}=6{\cdot}1\times10^{-1}\ B^{14/9} \quad . \ . \ . \quad (22)$$

and $\therefore$ for a fetch of 35 km, when $y=0{\cdot}73$,

$$W_{10}=0{\cdot}84\ B^{1{\cdot}56}$$

which is very similar to the relationship found by Simpson and adopted by the World Meteorological Organization. This suggests that in coastal waters the wind speed cannot be estimated from the appearance of the sea unless the fetch is also taken into account and that the Beaufort numbers can only be used for estimating the wind speed over the open oceans remote from land when the wind has been blowing long enough for a steady state to be obtained.

For the convenience of mariners Table VIII has been prepared from Table IV to give the equivalent wind speeds in knots.

TABLE VIII. *Beaufort numbers and suggested new equivalent wind speeds at a height of* 10 *m over open oceans*

Beaufort number	Knots	Knots rounded to nearest whole knot	Range in knots
0	0	0	<1
1	2·7	3	2–4
2	6·0	6	5–8
3	9·7	10	9–12
4	13·6	14	13–16
5	17·5+	18	17–20
6	21·7	22	21–24
7	26·0	26	25–28
8	30·3	30	29–32
9	34·8	35	33–36
10	39·4	39	37–41
11	43·9	44	42–46
12	48·7	49	47–51

CONCLUSIONS

1. With winds measured in metres per second at the internationally agreed height of 10 m above the sea the wind equivalents of the Beaufort numbers are for all practical purposes independent of the stability and are given by
   (i) $W=1{\cdot}38\,B^{7/6}$, which is a close approximation to the Seewarte series, over the open oceans, and
   (ii) $W=AB^{14/9}$ over coastal waters where A varies with the fetch, and W is equal to the international value with a fetch of about 35 km.
2. To quote Simpson[7]

   'The sailor's description of the strength of the wind being based on effects independent of the rig of his ship has survived all the changes in marine transport and an air, a breeze, a gale and a hurricane mean just the same to a sailor now as they did in Beaufort's time.'

The meteorologist has not been so fortunate but it seems that at long last after many vicissitudes the wind equivalents of the Beaufort numbers over the open oceans may mean the same to a meteorologist now as they did in the latter half of the nineteenth century.

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